

Probing Color Response - Wakes in a Color Plasma

Jörg Ruppert ^{† 1}

^{† ‡} Department of Physics, Duke University,
Science Drive, Box 90305, Durham 27707-0305, NC, USA

Abstract. The wake induced in a hot QCD medium by a high momentum parton (jet precursor) is calculated in the framework of linear response theory. Two different scenarios are discussed: a weakly coupled quark gluon plasma (pQGP) as described by hard-thermal loop (HTL) perturbation theory and a strongly coupled QGP (sQGP) with the properties of a quantum liquid. In the latter case the wake could exhibit a pronounced Mach cone structure. This physical mechanism could be important for the understanding of preliminary data from the PHENIX and STAR experiments at RHIC on the angular distribution of low-pt secondaries stemming from the away-side jet which indicate maxima at $\Delta\phi = \pi \pm 1.1$.

1. Introduction

QCD Jet quenching in relativistic heavy ion collisions has been proposed as an important possible signal of the creation of a quark-gluon plasma [1, 2]. It is extensively studied at RHIC.

The radiative energy loss of the leading parton due to the emission of a secondary partonic shower has been the main emphasis in the theoretical studies so far. For an overview of the quantum field theoretical calculations of the radiative energy loss and the experimental implications, see e. g. [3, 4, 5].

The study [6] focussed on a different aspect of the QCD jet physics in medium, namely the properties of the wake of current density, charge density and (chromo-)electric and magnetic field configurations that is induced by a charged particle traveling through a QCD medium with high momentum. The present contribution relies on that work [6].

The coherent behavior of the plasma as a reaction of a charged particle traveling through it is investigated by calculating the plasma's response to that external current. The calculation is restricted to only one weak, external current which points in a fixed direction in color group space. Methods of linear response theory are applied. The medium is assumed to be isotropic and homogenous. In such a framework quantum and non-abelian effects are included indirectly via the dielectric functions, ϵ_L and ϵ_T . Linear response theory implies that the dielectric functions are not in turn modified by the effects of the external current.

Two qualitatively different scenarios are investigated: In the first one, one assume that the plasmon is in a high temperature regime. There the gluon self-energies can be described using a high temperature expansion [7, 8] $T \gg \omega, k$. In the second scenario we study what are the significant physical effects if the plasma is strongly coupled (sQGP). In that scenario the plasma might be described best in terms of a quantum liquid.

It will be shown that the wake of a jet in such a quantum liquid can exhibit a characteristic cone-structure in the charge- and current-densities under certain conditions for the plasmon's

¹ email:ruppert@phy.duke.edu

dispersion relation and assuming a ‘supersonic’ velocity of the jet. Since it can be expected that the phenomenon of these Mach-cones leads to correlations in the directed emission of secondary partons from the plasmon. Observable consequences for particle correlations of this effect will be discussed in detail later in the present contribution.

The idea of determining the sound velocity of plasmon excitations of the expanding plasma from the emission pattern of the plasma particles traveling at an angle with respect to the jet axis has been discussed in [9, 10]. Our consideration of Mach-cones have also been motivated in parts by earlier studies of wakes induced by fast electrically charged projectiles in the electron plasma of metallic targets [11, 12], as well as by recent work exploring the induction of a conical flow by a jet in a sQGP [13]. This latter study invokes a hydrodynamical description of the energy deposited by a quenched jet in the medium and emphasizes the emergence of a Mach cone.

This proceeding contribution is organized as follows: first, in section 2, I give a short reminder of some general properties of plasma physics and derive the equation for the induced charge- and current-density in the considered situation. In section 3 I discuss the wake as obtained in a pQGP. In section 4 the wake obtained in a strongly coupled QGP is discussed. Possible observable consequences for particle correlations are studied in section 5. In section 6 I end with conclusions and a short acknowledgment.

The reader solely interested in the *results* related to a Mach cone structure might actually skip the next two sections and continue at section 4.

2. Plasma physics

The formalism for linear response theory of a plasma can straightforwardly be generalized from electromagnetic plasma physics (see e. g. [14]).

A dielectric medium can be characterized by the components the dielectric tensor ϵ_{ij} , which can be decomposed into ϵ_L and ϵ_T for an isotropic and homogenous medium via the longitudinal and transverse orthonormal projectors $\mathcal{P}_{L,ij} = k_i k_j / k^2$ and $\mathcal{P}_T = 1 - \mathcal{P}_L$ with respect to the momentum vector \vec{k} . Invoking a quantum field theoretical description one can relate these dielectric functions to the self-energies Π_L and Π_T of the in-medium gluon [15]

$$\epsilon_L(\omega, k) = 1 - \frac{\Pi_L(\omega, k)}{K^2}, \quad (1)$$

$$\epsilon_T(\omega, k) = 1 - \frac{\Pi_T(\omega, k)}{\omega^2}, \quad (2)$$

where $K^2 = \omega^2 - k^2$.

The knowledge of these dielectric tensors allows to relate the external current \vec{j}_{ext} to the total chromoelectric field \vec{E}_{tot}^a in the QCD plasma via:

$$\left[\epsilon_L \mathcal{P}_L + \left(\epsilon_T - \frac{k^2}{\omega^2} \right) \mathcal{P}_T \right] \vec{E}_{\text{tot}}^a(\omega, \vec{k}) = \frac{4\pi}{i\omega} \vec{j}_{\text{ext}}^a(\omega, \vec{k}). \quad (3)$$

The color charge induced by the external charge distribution is

$$\rho_{\text{ind}} = \left(\frac{1}{\epsilon_L} - 1 \right) \rho_{\text{ext}}. \quad (4)$$

The induced color charge density can also be calculated from the induced scalar potential via a Poisson equation:

$$\Phi_{\text{ind}} = \frac{4\pi}{k^2} \rho_{\text{ind}}, \quad (5)$$

if one works in a gauge where the vector potential is transverse to the momentum [16, 14].

Since one can relate the total chromo-electric field to the induced charge in linear response theory by

$$\vec{j}_{\text{ind}}^a = i\omega(1 - \epsilon)\vec{E}_{\text{tot}}^a/(4\pi), \quad (6)$$

a direct relation between the external and the induced current can be derived using Eqn. (3):

$$\vec{j}_{\text{ind}}^a = \left[\left(\frac{1}{\epsilon_L} - 1 \right) \mathcal{P}_L + \frac{1 - \epsilon_T}{\epsilon_T - \frac{k^2}{\omega^2}} \mathcal{P}_T \right] \vec{j}_{\text{ext}}^a. \quad (7)$$

The induced charge and the induced current obey a continuity equation:

$$i\vec{k} \cdot \vec{j}_{\text{ind}} - i\omega\rho_{\text{ind}} = 0. \quad (8)$$

For the following it is helpful to specify the current and charge densities associated with a color charge as Fourier transform of a point charge moving along a straight-line trajectory with constant velocity \vec{v} :

$$\vec{j}_{\text{ext}}^a = 2\pi q^a \vec{v} \delta(\omega - \vec{v} \cdot \vec{k}), \quad (9)$$

$$\vec{\rho}_{\text{ext}}^a = 2\pi q^a \delta(\omega - \vec{v} \cdot \vec{k}) \quad (10)$$

where q^a is its color charge defined by $q^a q^a = C\alpha_s$, with the strong coupling constant $\alpha_s = g^2/4\pi$ and the quadratic Casimir invariant C (which is either $C_F = 4/3$ for quarks or $C_A = 3$ for a gluon). In this model description changes of the color charge due to interactions while propagating through the medium are disregarded by fixing the charge's orientation in color space [7, 17] The induced charge- ρ_{ind} for this situation reads in cylindrical coordinates:

$$\rho_{\text{v,ind}}(\rho, z, t) = \frac{m_g^3}{(2\pi)^2 v} q^a \int_0^\infty d\kappa' \kappa' J_0(\kappa' \rho m_g) \int_{-\infty}^\infty d\omega' \exp \left[i\omega' \left(\frac{z}{v} - t \right) m_g \right] \left(\frac{1}{\epsilon_L} - 1 \right), \quad (11)$$

where $k = \sqrt{\kappa^2 + \omega^2/v^2}$, $\kappa = \kappa' m_g$ and $\omega = \omega' m_g$, showing that the induced charge density $\rho_{\text{v,ind}}$ is proportional to m_g^3 . The cylindrical symmetry around the jet axis restricts the form of the current density vector \vec{j}_{ind} . It has only non-vanishing components parallel to the beam axis, $\vec{j}_{\text{v,ind}}$, and radially perpendicular to it, $\vec{j}_{\rho,\text{ind}}$:

$$\begin{aligned} \vec{j}_{\text{v,ind}}(\rho, z, t) &= \frac{m_g^3}{(2\pi)^2 v^2} q^a \int_0^\infty d\kappa' \kappa' J_0(\kappa' \rho m_g) \times \\ &\quad \int_{-\infty}^\infty d\omega' \exp \left[i\omega' \left(\frac{z}{v} - t \right) m_g \right] \left[\left(\frac{1}{\epsilon_L} - 1 \right) \frac{\omega^2}{k^2} + \frac{1 - \epsilon_T}{\epsilon_T - \frac{k^2}{\omega^2}} \left(v^2 - \frac{\omega^2}{k^2} \right) \right], \\ \vec{j}_{\rho,\text{ind}}(\rho, z, t) &= \frac{im_g^3}{(2\pi)^2 v} q^a \int_0^\infty d\kappa' \kappa' J_1(\kappa' \rho m_g) \times \\ &\quad \int_{-\infty}^\infty d\omega' \exp \left[i\omega' \left(\frac{z}{v} - t \right) m_g \right] \frac{\omega \kappa}{k^2} \left[\left(\frac{1}{\epsilon_L} - 1 \right) - \left(\frac{1 - \epsilon_T}{\epsilon_T - \frac{k^2}{\omega^2}} \right) \right]. \end{aligned} \quad (12)$$

Again, the components of the current density are proportional to m_g^3 .

In order to deepen the understanding of the results obtained in the different scenarios it is helpful to discuss the corresponding plasmon dispersion relations for a given dielectric function.

In order to determine non-trivial solutions of Equation (3), the following determinant has to vanish:

$$\det \left| \epsilon_L \mathcal{P}_L + (\epsilon_T - \frac{k^2}{\omega^2}) \mathcal{P}_T \right| = 0. \quad (13)$$

This equation governs the dispersion relation for the waves in the medium. Since it can be diagonalized into purely longitudinal and transverse parts, dispersion relations for the longitudinal and transverse dielectric functions can be derived [14]:

$$\epsilon_L = 0, \quad (14)$$

$$\epsilon_T = (k/\omega)^2. \quad (15)$$

These equations determine the longitudinal and transverse plasma modes. The longitudinal equation is also the dispersion relation for density-fluctuations in the plasma, namely space-charge fields which could be spontaneously excited in the plasma without an application of external disturbances [14].

3. Charge wake in a QGP in the high temperature approximation

In this section the first scenario is studied in detail. Here the medium is assumed to be in the high temperature regime where the gluon self-energies are described by the leading order of the high temperature expansion $T \gg \omega, k$ [8, 7]. The self-energies derived within the HTL approximation have been shown to be gauge invariant [18] and the dielectric functions are therefore also gauge invariant. The dielectric functions read explicitly [15]:

$$\begin{aligned} \epsilon_L &= 1 + \frac{2m_g^2}{k^2} \left[1 - \frac{1}{2}x \left(\ln \left| \frac{x+1}{x-1} \right| - i\pi\Theta(1-x^2) \right) \right], \\ \epsilon_T &= 1 - \frac{m_g^2}{\omega^2} \left[x^2 + \frac{x(1-x^2)}{2} \left(\ln \left| \frac{x+1}{x-1} \right| - i\pi\Theta(1-x^2) \right) \right], \end{aligned} \quad (16)$$

where $x = \omega/k$.

These dielectric function leads to longitudinal and transverse plasma modes, that are determined by the dispersion relations (16). They can only appear in the time-like sector of the ω, k plane [7, 15], see Fig. 1. Collective excitations do not contribute to the charge and current density profile of the wake. Mach cones do not appear, but the charge carries a screening color cloud along with it. Fig. 2 illustrates this physically intuitive result numerically. It shows the charge density of a colored parton traveling with $v = 0.99c$ in cylindrical coordinates. The screening cloud is concentrated in the vicinity of the particle. In the static case where the current density vector vanishes, the induced charge density can be calculated analytically, it has a Yukawa-like shape $\propto \exp(-\sqrt{2m_g r})$.

Despite the fact that Mach cones do not appear in the charge density wake, the particle still suffers energy loss due to elastic collisions in the medium. This effect of energy dissipation has been studied in [17] in detail. The integrand determining the energy loss [17] contributes only where $|x| < 1$, and therefore does not get contributions from frequencies where collective plasma modes exist. This is consistent with the fact that such modes are not excited in the induced charge and current densities.

4. Charge wake induced in a strongly coupled QGP

Here we assume that the plasma is in a strongly coupled regime having properties of a quantum liquid. Since there is a lack of theoretical methods for first principle calculations for the dielectric

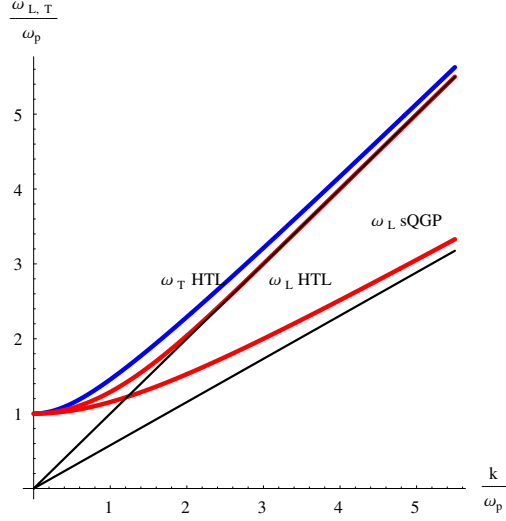


Figure 1. Longitudinal and transverse plasmon-branches in the ω , k -plane for a pQGP (calculation in the HTL approximation) and in the sQGP framework as studied in section 4 for (see Eqn. (17) for $u^2 = 1/\sqrt{3}$). Note that the pQGP plasmon-branches are only in the time-like region of the plane whereas the sQGP longitudinal plasmon branch extends above $k > \omega_p/\sqrt{1-u^2}$ into the space-like region. The straight lines indicate $\omega = k$ and $\omega = uk$.

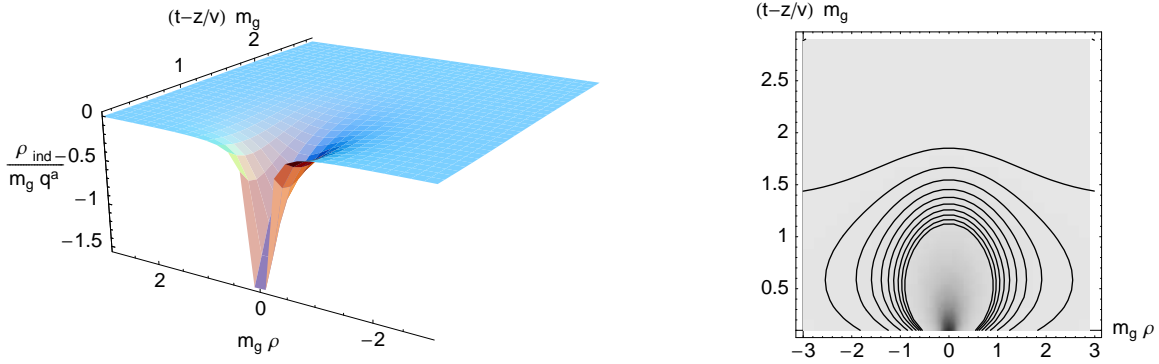


Figure 2. Spatial distribution of the induced charge density from a jet with fixed color charge q^a in a high temperature plasma where the HTL approximation is applicable. The right plot shows equi-charge lines in the density distribution. The density profile is a cloud traveling with the color charged jet.

functions in this regime, we use a simple model calculation in this scenario. Nonetheless, the simplified model is constructed in such a way that it allows for general conclusion quite independent from the exact form of the dielectric functions.

The notion of a sQGP suggest low dissipation at small momenta (‘hydro modes’) and large dissipation at high k_c . The existence of a critical momentum k_c is assumed which separates the regimes of collective and single particle modes in the quantum liquid. Below k_c are plasmon excitations and dissipation is assumed to be negligible for simplicity. Since we are interested in collective effects, the region above k_c is neglected.

To be specific, it is assumed that the longitudinal dielectric function of the strongly coupled plasma in the $k < k_c$ regime is

$$\omega_L = \sqrt{u^2 k^2 + \omega_p^2}, \quad (17)$$

where ω_p denotes the plasma frequency and u the speed of plasmon propagation which is assumed to be constant. The most important property of this dispersion relation for our purposes is, that it extends into the space-like region of the ω, k plane above some k . For the dispersion relation (17) this is the case for $k > \omega_p/\sqrt{(1-u^2)}$. This is different for the high-temperature plasma, where longitudinal and transverse plasma modes only appear in the time-like region, $|x| = |\omega/k| > 1$. In the quantum liquid scenario one can expect that the modes with low phase velocity $|x| < u$ suffer severe Landau damping because they accelerate the slower moving charges and decelerate those moving faster than the wave [7, 14]. A charge moving with a velocity that is lower than the speed of plasmon propagation can only excite these modes and not the modes with intermediate phase velocities $u < |x| < 1$, which are undamped [14, 7]. The qualitative properties of the color wake can in this case expected to be analogous to those of the high temperature plasma, namely that the charge carries only a screening color cloud with it and Mach cones do not appear.

If the colored parton travels with a velocity $v > u$ that is higher than the speed of sound in the medium, modes with an intermediate phase velocity $u < |x| < 1$ can be excited. The emission of these plasma oscillations induced by supersonically traveling particles is analogous to Cherenkov radiation. This can be expected to lead to the emergence of Mach cones in the induced charge density cloud with the opening angle

$$\Delta\Phi = \arccos(u/v). \quad (18)$$

The effect is well known in solid state physics [14] and is analogous to the Mach cones induced by fast heavy ions in electron plasmas [11, 12, 19]. The physics of shock waves in relativistic heavy-ion collisions has also been discussed in [20, 21, 22].

To be specific the following dielectric function is assumed in accordance with (17):

$$\epsilon_L = 1 + \frac{\omega_p^2/2}{u^2 k^2 - \omega^2 + \omega_p^2/2} \quad (k \leq k_c). \quad (19)$$

Note that this differs from the classical, hydrodynamical dielectric function of Bloch [23], since the latter one is singular at small k and ω due to phonon contributions which cannot mix with colored plasmons.

This dielectric function (19) has the plasmon mode (see Eqn. 17) which extends into the space-like region of the ω, k plane, see Fig. 1. The qualitative induced wake structure in such a quantum liquid scenario is general, namely a Mach shock wave structure for a ‘supersonically’ traveling color source as discussed above. In that sense the principal findings can be expected to hold generally for a quantum liquid with a plasmon branch similar to (19) independent of the exact form of the dielectric function.

To be specific a speed of plasmon propagation of $u/c = 1/\sqrt{3}$ is assumed (compared that to $u/c = \sqrt{3/5}$ in the HTL approximation and to $u/c \approx \sqrt{0.2}$ [24, 25] for a hadron resonance gas).

Figures 4a,b show the induced charge density for a colored particle traveling ‘supersonically’ at $v = 0.99c > u$ which is calculated using eq. (11). The integration area has been restricted to the region $k < k_c = 2\omega_p^2$. Numerical consistency has been checked also via calculation of the induced current densities and the continuity equation. On the other hand a ‘subsonically’ traveling particle with $v = 0.55c < u$ induces a charge density profile which is qualitatively analogous to the high-temperature plasma, namely a comoving screening cloud, see Fig. 3.

² Note that the expressions in [11, 12] do not correspond to $k < k_c$, but $\kappa < k_c$.

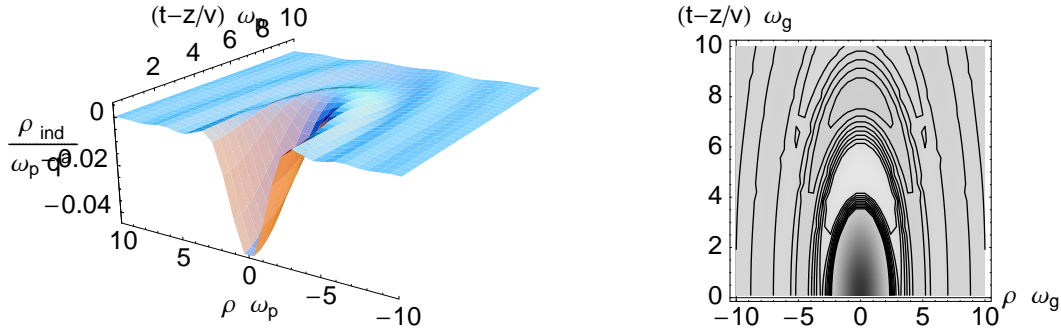


Figure 3. Spatial distribution of a induced charge density from a jet with high momentum and a fixed color charge q^a that is traveling with $v = 0.55c < u$. The right plot shows equi-charge lines in the density distribution. The density profile is that of a cloud traveling with the color charged jet.

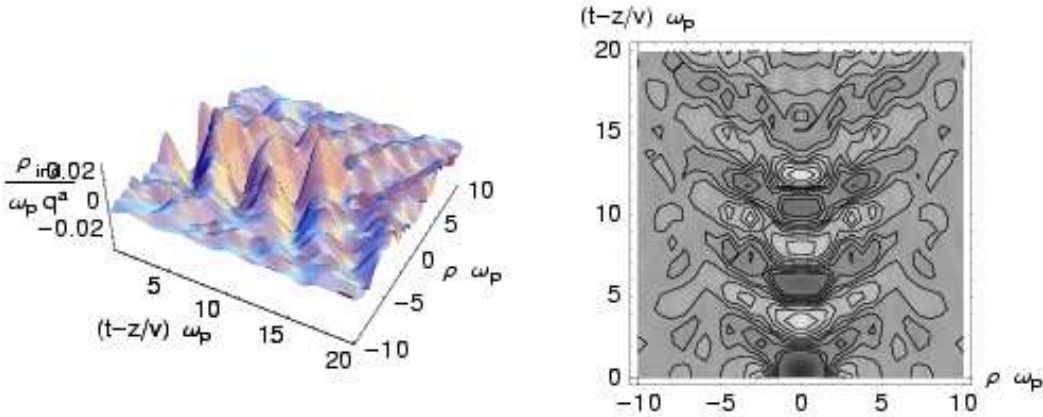


Figure 4. Spatial distribution of the induced charge density from a jet with high momentum and fixed color charge q^a that is traveling with $v = 0.99c > u = \sqrt{1/3}c$. The right plot shows equi-charge lines in the density distribution.

5. Observable consequences

It can be expected that the phenomenon of Mach cones in the charge density translates into Mach cones in the particle density and should eventually lead to a directed emission of secondary partons from the plasma. This effect has an analogy in solid state physics where Mach cones induced by fast heavy ions in an electron plasma lead to an emission of electrons that have been carried within the wake [11, 12]. This effect has been studied experimentally [19].

If that scenario of a strongly coupled QCD plasma is realized in the matter created in an ultrarelativistic heavy ion collision, one could expect to observe these cones in the actual distribution of secondary particles associated with jets at RHIC, a signature also proposed in [9, 13].

Indeed preliminary data from the PHENIX and STAR experiments (see e.g. Fig. 1 in [26] and preliminary data from PHENIX) show such effects in the background distribution of secondary particles in the azimuthal angle $\Delta\phi$. The peak near zero degree corresponds to secondaries from the outmoving jet, particles from the companion jet result in a distribution with a clear maximum near $\Delta\phi = \pi$ for pp collisions, where no medium effects are present. In Au-Au collisions there is a distribution with two maxima around the $\Delta\phi = \pi$ position. These are

located at $\Delta\phi \approx \pi \pm 1.1$. One can argue [13] that such an effect could possibly be traced back to a Mach shock front (predicted in a hydrodynamical framework) traveling with the side-away jet leading to maxima in the distribution at about $\Delta\Phi = \pi \pm \arccos(u/v)$.

Given the confirmation of this effect in the data mentioned, this would clearly indicate that the first scenario, viz. a pQCD plasma, is not realized in RHIC experiments. A further decision on the possible occurrence of Mach cone structures could be deduced by studying correlations in the secondaries as proposed by the PHENIX collaboration. Indication of such a Mach cone structure could reveal properties of the plasma and its plasmons in general, which is a fascinating perspective. The speed of plasma propagation could be also determined. In fact if the maxima at $\Delta\phi \approx \pi \pm 1.1$ are experimentally confirmed, it would correspond to $u/c \approx \sqrt{0.2}$ [13]. It is interesting to note, that a study of the angular structure of the collisional energy losses of a hard jet in the medium would also support such an observation: the incident hard jet's scattering angle vanishes in the relativistic limit - leading to the jet's propagation along a straight line - whereas the expectation value of the scattering angle Θ of a struck "thermal" particle is $\langle\Theta\rangle \approx 1.04$ [27] which is close to 1.1.

6. Conclusions

The properties of the charge density wake of a colored hard partonic jet traveling through a QGP plasma in the framework of linear response theory has been discussed. Two different scenarios have been studied, namely a high temperature QGP at $T \gg T_c$ described in the HTL approximation, and a description of a strongly coupled QGP (sQGP) behaving as a quantum liquid. It was found that the structure of the wake corresponds to a screening color cloud traveling with the particle in the case of the high temperature plasma and in the case of a quantum fluid, if the velocity of sound in the plasma is not exceeded by the jet in the latter case. The structure of the wake is changed considerably in comparison to the former cases, if the jet's velocity exceeds the plasma's speed of sound and the collective modes have a dispersion relation extending in the space-like region. Then the induced parton density exhibits the characteristics of Mach waves trailing the jet at the Mach angle.

It is argued that this effect could be used to constrain theoretically possible scenarios by experimental analysis via the measurements of angular distribution of the secondary particle cones of jet events in RHIC. First indications of the observation of a Mach shock phenomenon in RHIC in the quenched jet's secondary particle distribution from PHENIX and STAR data were discussed.

In general secondary particle distributions can be used to provide methods of probing the QCD plasma's collective excitations experimentally.

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